Quantum Electronics **46** (4) 371 – 374 (2016)

DOI: 10.1070/QEL16052

Nd : glass rod laser with an output energy of 500 J

A.A. Shaykin, A.A. Kuzmin, I.A. Shaikin, K.F. Burdonov, E.A. Khazanov

Abstract. **The energy of two orthogonally polarised pulses injected into an available multistage amplifier based on neodymium phosphate glass rods was increased from 300 to 500 J (in both pulses). The second output pulse with an energy of 200 J will be used to pump an additional parametric amplifier of a petawatt laser.**

Keywords: *laser amplifier, neodymium phosphate glass, petawatt laser.*

1. Introduction

Neodymium laser glass as an active medium for nano- and picosecond lasers with a pulse energy exceeding 100 J has almost no alternative. These lasers are widely used to excite and study shock waves in solids [1], to test the optical strength of wide-aperture elements [2, 3], to simulate effects in high-energy physics and laser ICF [4, 5], and in other cases [6, 7]. One of the main applications is generation of petawatt pulses [8, 9], as well as pumping of petawatt and multipetawatt parametric amplifiers [10 – 14] and Ti : sapphire amplifiers [15 – 18].

There exist two geometries of active elements of high-power neodymium lasers, namely, rod and slab geometries. The advantages of the first one are single-pass amplification, better output beam quality, compactness, simple alignment, and higher pulse repetition rate. At the same time, slabs allow one to achieve a higher pulse energy due to large apertures (up to 40×40 cm), because the factors limiting the pulse energy are optical breakdown and small-scale self-focusing. The maximum diameter of rods used in amplifiers is 15 cm [19], but fabrication of these rods requires unique technologies. At present, the maximum diameter used in practice is 9 – 10 cm [13, 14, 20, 21]. The limitation of the aperture size is especially negative for amplifiers of chirped pulses and for pump lasers of parametric amplifiers because of a short (1 ns) pulse duration. At this duration, the maximum pulse energy is limited at a level of 300 J, although the stored energy is much higher.

In [22], it was proposed to amplify two successive pulses instead of one pulse, which, first, considerably simplifies the formation of rectangular output pulses and, second, makes it possible to strongly increase the total output energy, because the above restrictions are imposed on one pulse. In the present work, we used the second advantage and injected two orthogonally polarised pulses into an available multistage amplifier. Without increasing the number of amplifiers and their gains, we obtained both an output pulse with an energy of 300 J and an additional output pulse with an energy of 200 J, which will be used to pump an additional parametric amplifier.

2. Laser scheme

Figure 1 presents the scheme of a setup consisting of two parts, namely, a system generating two replicas of the input pulse and a multistage laser amplifier. The input pulse from a master oscillator and a preamplifier (not shown in Fig. 1) had an energy up to 4.5 mJ, a duration of 1.5 ns, and a beam diameter of 10 mm.

The wave vector directions of the two pulses injected into the multistage amplifier must coincide with an error much smaller than the diffraction-limited divergence. The energy of the first pulse must be considerably lower than the second pulse energy because, due to saturation of amplifiers, the second pulse is amplified considerably weaker. A smooth change in the energy ratio of the input pulses enables one to smoothly change their energy ratio at the exit from the amplifiers.

There exist two principally different methods of generation of two replicas of the input pulse, i.e., an amplitude method (by splitting the beam and then superimposing the beams by semitransparent mirrors) and a polarisation method (using polarisers). In the first case, the pulses have identical polarisations, and this imposes weaker restrictions on the optical units of the amplifying channel, for example, allows the use of polarisers, which is impossible in the case of polarisation splitters. In addition, the amplitude method, in contrast to the polarisation one, can be used to obtain three and more pulses. However, its application is accompanied by energy losses, while the total energy of the two pulses injected into amplifiers in the case of the polarisation method is almost equal to the energy of the input pulse. But the main difference in these approaches is that the two pulses at the exit from the amplifier in the case of the polarisation method have orthogonal polarisations. This can be both an advantage and a drawback (depending on applications). In our case, we chose the polarisation method because, to pump two parametric amplifiers, it is convenient to spatially separate the output pulses, which is impossible if the two pulses are identically polarised.

The energy ratio of the two input pulses ($E_{\mathrm{in}2}$ and $E_{\mathrm{in}1}$) was changed by rotating a half-wave plate (Fig. 1). The delay between the pulses was 7 ns. On the one hand, this time considerably exceeds the pulse duration and allows one to expect that the 300-J limit of the maximum energy will be imposed

---

A.A. Shaykin, A.A. Kuzmin, I.A. Shaikin, K.F. Burdonov, E.A. Khazanov Institute of Applied Physics, Russian Academy of Sciences, ul. Ul'yanova 46, 603950 Nizhnii Novgorod, Russia; e-mail: khazanov@appl.sci-nnov.ru

Received 8 February 2016
Kvantovaya Elektronika **46** (4) 371 – 374 (2016)
Translated by M.N. Basieva

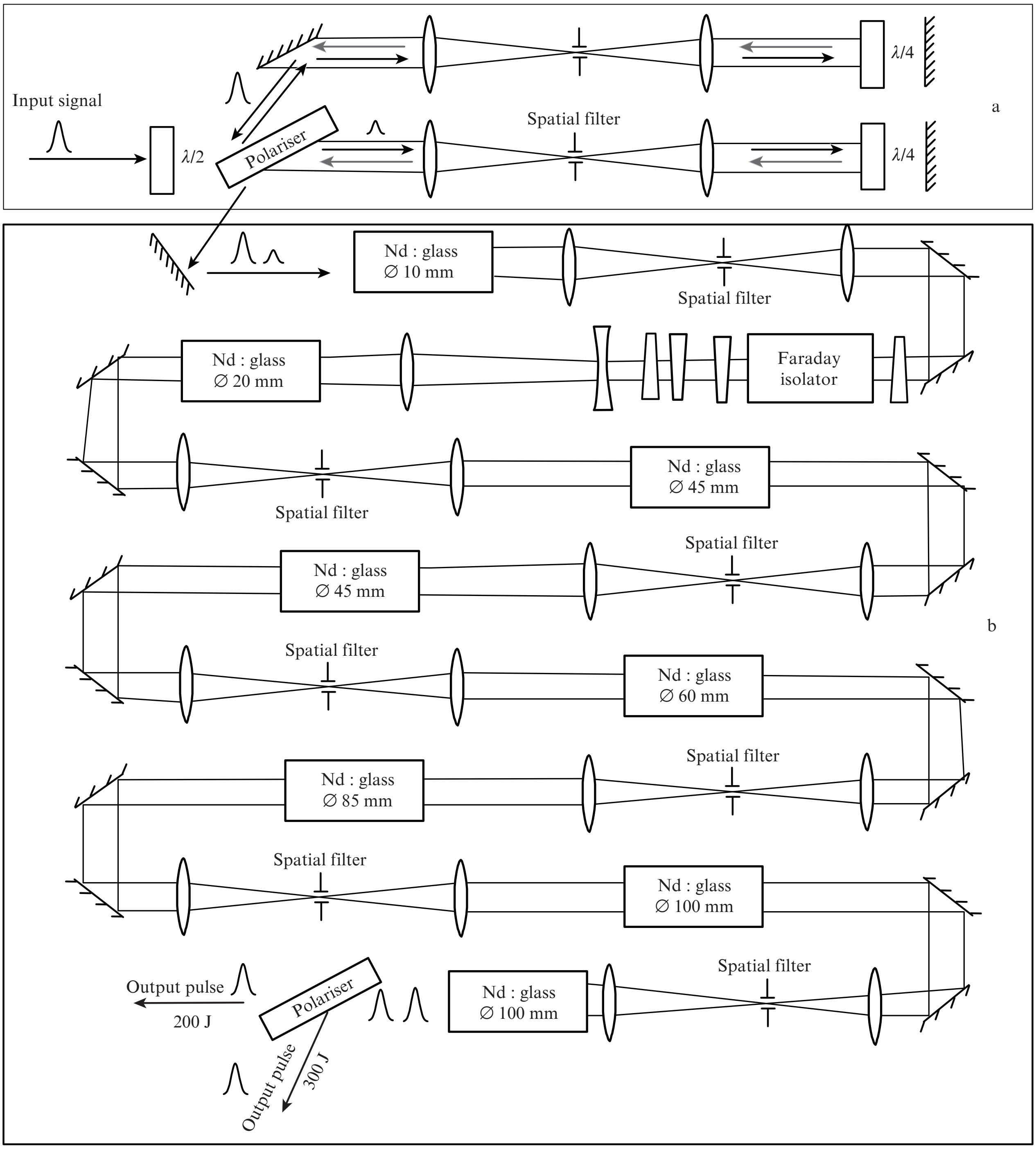

Figure 1. Scheme of the setup: (a) system generating two replicas of the input signal and (b) multistage laser amplifier.

separately on each pulse. On the other hand, this delay time is smaller than the time of plasma formation in the apertures of spatial filters (see below), which lets the second pulse freely propagate through the filters.

Each of the pulses leaving the polarisation beam splitter doubly passes through a telescope. This two-pass geometry ensures the maximally compact transfer of the image of the output plane of the preamplifier (not shown in Fig. 1) to the entrance of the amplifier with a rod with a diameter of 10 mm.

After superimposition of the two beams on a polariser, they were sent to a multistage neodymium phosphate glass amplifier. All the units of the amplifier will be described in detail in a separate publication, while in the present work we restrict ourselves to a short description of the main units. The eight amplifiers were based on rods with diameters of 10, 20, 45, 45, 60, 85, 100, and 100 mm. Vacuum spatial filters were placed between them to transfer images from one amplifier to another. The voltage of the power supply units for amplifiers with 10-, 20-, and 45-mm-diameter rods was constant and equal to 4.5, 4.5, and 5.5 kV, respectively. On all the other amplifiers, we applied identical voltages of 11, 11.5, and 12.5 kV in each shot in the process of measurements. As polarisers in the Faraday isolator, we used calcite wedges. An additional pair of calcite wedges placed behind the isolator allowed the two pulses to propagate through the amplifier despite their orthogonal polarisations. The isolator suppressed self-excitation at the maximum pump power of all the amplifiers, at which the total small-signal gain was 3×10^7. Note that, due to the Fresnel losses and absorption in glass, the transmission of the system from the entrance to the exit was 0.14. At the exit of the last amplifier, the pulses were split by a polariser and sent for diagnostics. The amplifiers were mounted on an optical table with dimensions of 10×1.7 m.

3. Experimental results and discussion

At the exit of the amplifier, we measured both the energy of each pulse $E_{\rm out1}$ and $E_{\rm out2}$ and the total energy $E_{\rm out} = E_{\rm out1} + E_{\rm out2}$. Figure 2 shows the dependences of these energies on the input energy $E_{\rm in} = E_{\rm in1} + E_{\rm in2}$ at the voltages of the energy supply units $U = 11$, 11.5, and 12.5 kV. It is seen that, at $E_{\rm in} \approx 1.5$ mJ, the total output energy $E_{\rm out}$ levels off at approximately 400, 450, and 500 J for $U = 11$, 11.5, and 12.5 kV, respectively, which agrees with the results of theoretical calculations. Note that the second pulse freely passes through all the spatial filters even at the maximum energy, i.e., the plasma formation time in their apertures exceeds 7 ns (see Fig. 3b).

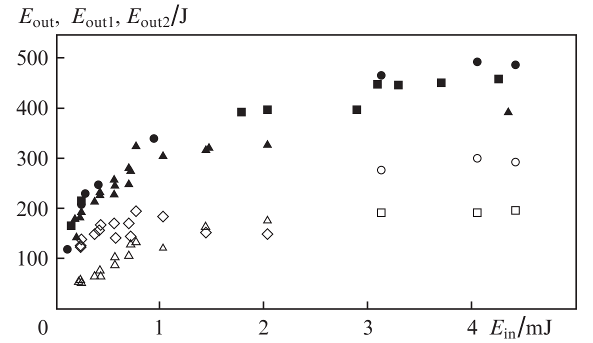

Figure 2. Dependences $E_{\rm out}(E_{\rm in})$ at U (▲) = 11, (■) 11.5, and (●) 12.5 kV, as well as dependences (△, ○) $E_{\rm out1}(E_{\rm in})$ and (◇, □) $E_{\rm out2}(E_{\rm in})$ for (△, ◇) $E_{\rm in2}/E_{\rm in1} = 5$, $U = 11$ and (○, □) $E_{\rm in2}/E_{\rm in1} = 10$, $U = 12.5$ kV.

Figure 2 shows the dependences $E_{\rm out1}(E_{\rm in})$ and $E_{\rm out2}(E_{\rm in})$ for the ratios $E_{\rm in2}/E_{\rm in1} = 5$ (at $U = 11$ kV) and $E_{\rm in2}/E_{\rm in1} = 10$ (at $U = 12.5$ kV). To not overload the figure, these dependences for other values of $E_{\rm in2}/E_{\rm in1}$ and U are not shown. At $U = 11$ kV, the first pulse is linearly amplified at $E_{\rm in} < 0.6$ (i.e., $E_{\rm in1} < 0.1$ mJ), but at higher $E_{\rm in}$ its saturation is already pronounced. The second pulse exhibits saturation even at $E_{\rm in} = 0.2$ mJ because its input energy is considerably higher. With increasing $E_{\rm in}$, the energy $E_{\rm out2}$ not only does not saturate but even reaches a maximum and begins to decrease, because the first pulse considerably depletes the inversion.

At high $E_{\rm in}$ and $U = 12.5$ kV, the ratio $E_{\rm in2}/E_{\rm in1} = 10$ was chosen so that the first pulse $E_{\rm out1}$ was close to 300 J, i.e., to the maximum energy at which breakdown does not yet occur. In this case, the energy of the second pulse was about 200 J. According to calculations, a further increase in $E_{\rm in}$ causes no considerable increase in both $E_{\rm out1}$ and $E_{\rm out2}$. Moreover, the inversion remaining in the last amplifier after the first pulse is so low that the amplification of the second pulse is almost compensated by the Fresnel losses and absorption in the glass. Therefore, we plan to place a polariser in front of the last amplifier, send the pulse reflected from this polariser to an additional amplifier, and thus achieve the maximum permissible energy of 300 mJ in each of the two pulses.

Figure 3 shows the near-field intensity distributions and the oscillogram of the output beams with energies of 300 and 195 J. The beam quality can be improved by more precise alignment and by profiling the input beam. The oscillograms of pulses were measured by a photodiode with a resolution of 300 ps and an oscilloscope with a bandwidth of 1 GHz.

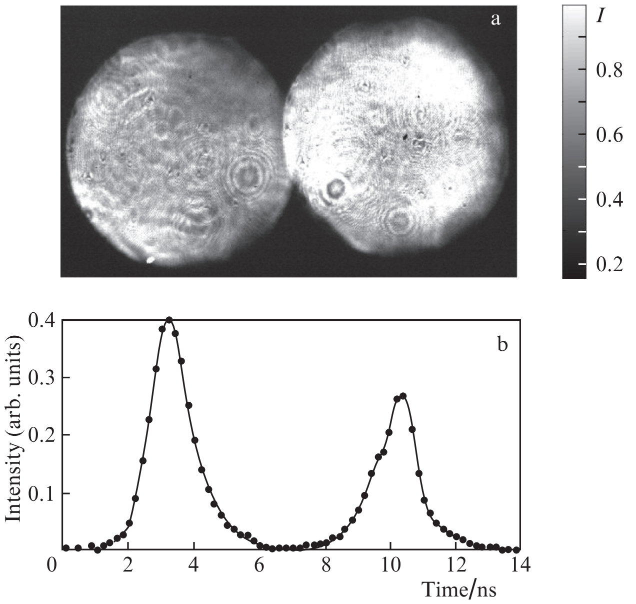

Figure 3. Output intensity distributions (a) in the near-field zone and (b) in time. The energies of pulses are 300 and 200 J; the beam diameter is 100 mm.

After frequency doubling, the durations of pulses will decrease to 1.2 ns, and they will be used for pumping two parametric amplifiers of a petawatt laser: the first pulse will, as before [11], pump the first amplifier, and the second pulse will pump an additional amplifier, which will lead to a considerable increase in the power of the output femtosecond pulse.

In conclusion, note that this amplifier scheme compared to the scheme of an amplifier used in a three-hundred-joule pump laser used in [13], apart from the additional 200 J pulse, has one more advantage, namely, much lower distortions of the pulse shape. This considerably simplifies the formation of rectangular output pulses. The performed calculations showed that the distortion coefficient (ratio of the gain at the leading edge to the gain at the trailing edge) for the 300-J pulse in this laser is 22, while this coefficient for the laser from [13] was 80. In the present work, this advantage was unimportant because the pulse was bell-shaped (Fig. 3b), but in the future we plan to use this advantage to form rectangular output pulses, which will increase the efficiency of both frequency doubling and parametric amplification.

Thus, since the optical strength of the laser glass rod 100 mm in diameter limits the energy of 1-ns laser pulses by 300 J, in this work we used the injection of two successive pulses into a multistage amplifier, which allowed us to obtain an output energy of 500 J (300 J in the first pulse and 200 J in the second). A further increase in the energy can be achieved by partitioning the output amplifier into two amplifiers, in which the pulses will be amplified in parallel, as well as by increasing the aperture of the output amplifiers to 150 mm.

Acknowledgements. This work was supported by the 'Extreme Laser Radiation: Physics And Fundamental Applications' Programme of the Presidium of the Russian Academy of Sciences and by the Ministry of Education and Science of the Russian Federation (Project No. 14.Z50.31.0007). The fabrication of the experimental setup was supported by the Russian Foundation for Basic Research (Grant Nos 15-02-08099 and 16-32-60125).

References

1. Krasyuk I.K. *Usp. Fiz. Nauk*, **169**, 1155 (1999).
2. Nostrand M.C., Weiland T.L., Luthi R.L., Vickers J.L., Sell W.D., Stanley J.A., Honig J., Auerbach J.M., Hackel R.P., Wegner P.J. *Proc. SPIE Int. Soc. Opt. Eng.*, **5273**, 325 (2003).
3. Lamaignere L., Dupuy G., Bourgeade A., Benoist A., Roques A., Courchinoux R. *Appl. Phys. B*, **114**, 517 (2014).
4. Norman M.J., Andrew J.E., Bett T.H., Clifford R.K., England J.E., Hopps N.W., Parker K.W., Porter K., Stevenson M. *Appl. Opt.*, **41**, 3497 (2002).
5. Rambo P.K., Smith I.C., Porter J.L., Hurst M.J., Speas C.S., Adams R.G., Garcia A.J., Dawson E., Thurston B.D., Wakefield C., Kellogg J.W., Slattery M.J., Ives III H.C., Broyles R.S., Caird J.A., Erlandson A.C., Murray J.E., Behrendt W.C., Neilsen N.D., Narduzzi J.M. *Appl. Opt.*, **44**, 2421 (2005).
6. Remo J.L., Adams R.G. *Proc. SPIE Int. Soc. Opt. Eng.*, **7005**, 70052M (2008).
7. Brown M., Ekberg J.O., Feldman U., Seely J.F., Richardson M.C., Marshall F.J., Behring W.E. *J. Opt. Soc. Am. B*, **4**, 533 (1987).
8. Gaul E., Martinez M., Blakeney J., Jochmann A., Ringuette M., Hammond D., Borger T., Escamilla R., Douglas S., Henderson W., Dyer G., Erlandson A., Cross R., Caird J., Ebbers C.A., Ditmire T. *Appl. Opt.*, **49**, 1676 (2010).
9. Perry M.D., Pennington D., Stuart B.C., Tietbohl G., Britten J.A., Brown C., Herman S., Golick B., Kartz M., Miller J., Powell H.T., Vergino M., Yvanovsky V. *Opt. Lett.*, **24**, 160 (1999).
10. Chekhlov O.V., Collier J.L., Ross I.N., Bates P.K., Notley M., Hernandez-Gomez C., Shaikh W., Danson C.N., Neely D., Matousek P., Hancock S. *Opt. Lett.*, **31**, 3665 (2006).
11. Lozhkarev V.V., Freidman G.I., Ginzburg V.N., Katin E.V., Khazanov E.A., Kirsanov A.V., Luchinin G.A., Mal'shakov A.N., Martyanov M.A., Palashov O.V., Poteomkin A.K., Sergeev A.M., Shaykin A.A., Yakovlev I.V. *Laser Phys. Lett.*, **4**, 421 (2007).
12. Xu L., Yu L., Liang X., Chu Y., Hu Z., Ma L., Xu Y., Wang C., Lu X., Lu H., Yue Y., Zhao Y., Fan F., Tu H., Leng Y., Li R., Xu Z. *Opt. Lett.*, **38**, 4837 (2013).
13. Poteomkin A.K., Khazanov E.A., Martyanov M.A., Kirsanov A.V., Shaykin A.A. *IEEE J. Quantum Electron.*, **45**, 854 (2009).
14. Potemkin A.K., Katin E.V., Kirsanov A.V., Luchinin G.A., Mal'shakov A.N., Mart'yanov M.A., Matveev A.Z., Palashov O.V., Khazanov E.A., Shaykin A.A. *Kvantovaya Elektron.*, **35**, 302 (2005) [*Quantum. Electron.*, **35**, 302 (2005)].
15. Kiriyama H., Michiaki M., Nakai Y., Shimomura T., Sasao H., Tanaka M., Ochi Y., Tanoue M., Okada H., Kondo S., Kanazawa S., Sagisaka A., Daito I., Wakai D., Sasao F., Suzuki M., Kotakai H., Kondo K., Sugiyama A., Bulanov S., Bolton P.R., Daido H., Kawanishi S., Collier J.L., Hernandez-Gomez C., Hooker C.J., Ertel K., Kimura T., Tajima T. *Appl. Opt.*, **49**, 2105 (2010).
16. Yanovsky V., Alinchenko G., Rousseau P., Chvykov V., Mourou G., Krushelnick K. *Appl. Opt.*, **47**, 1968 (2008).
17. Kuzmin A.A., Khazanov E.A., Kulagin O.V., Shaykin A.A. *Opt. Express*, **22**, 20842 (2014).
18. Kuz'min A.A., Kulagin O.V., Khazanov E.A., Shaykin A.A. *Kvantovaya Elektron.*, **43**, 597 (2013) [*Quantum. Electron.*, **43**, 597 (2013)].
19. Shaykin A.A., Fokin A.P., Solov'ev A.A., Kuz'min A.A., Shaykin I.A., Burdonov K.F., Charukhchev A.V., Khazanov E.A. *Kvantovaya Elektron.*, **44**, 426 (2014) [*Quantum. Electron.*, **44**, 426 (2014)].
20. Bayanov V.I., Borodachev E.G., Volynkin V.M., Kryzhanovskii V.I., Mak A.A., Motorin I.V., Nikonova M.V., Serebryakov V.A., Starikov A.D., Charukhchev A.V., Shchavelev O.S., Yashin V.E. *Kvantovaya Elektron.*, **13**, 1891 (1986) [*Sov. J. Quantum. Electron.*, **16**, 1240 (1986)].
21. Kong H.J., Lee S.S., Kim H.S., Han K.G., Kim N.S., Um K.Y., Park J.R., Lee J.Y. *Laser Part. Beams*, **15**, 317 (1997).
22. Shaykin A.A. *Kvantovaya Elektron.*, **44**, 440 (2014) [*Quantum. Electron.*, **44**, 440 (2014)].